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Foam fluid flow analysis in helical coiled tubing using CFD

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Abstract

Coiled tubing (CT) technology has developed rapidly and widely used in drilling, completion, oil test, production. Foam is a gas-liquid dispersion. The excellent properties of foam fluid are useful but it is difficult to simulate it. At present, Foam fluid combined with CT is used in well intervention as a practical and cost-effective mean of servicing wells. This paper discusses the flow law of foam fluid in coiled tubing through user defined function and numerical simulation method combining the characteristics of foam fluid. First, the rheology of foam is described by Power-law model, Then, a function about density of foam fluid is obtained by considering the pressure and temperature. After that, the geometric model of helical coiled tubing is established, According to hydrodynamic theory, based on continuity equation and N-S equation, the numerical simulation for foam fluid flow in helical CT is carried out. The results show that pressure and velocity are reducing along the helical coiled tubing from entrance to export. The velocity closed outside of the helical coiled tubing is larger than that closed inside of it. Moreover, the secondary flow appears in the cross section of the helical coiled tubing as vortex roll, and the configuration of vortex roll of foam fluid is smaller than that of water fluid.

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Keywords: coiled tubing; foam fluid; numerical simulation; flow distribution; secondary flow

1. Introduction

Coiled tubing (CT) technology has been applied for more than 50 years. With its few occupied space, low operation cost, convenient transportation, recovery increasing of oil wells and many other advantages, CT technology has developed rapidly and widely used in drilling, completion, oil test, production[1-4]. Practical application shows that the coiled tubing technology is a great potential practical technology.

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Foam is a gas-liquid dispersion in which the liquid is the continuous phase and the gas is the discontinuous phase. In recent years, foam fluids are widely used in simulation treatments as intelligent fluid attributed to their properties, such as low density, high viscosity. Besides, foam fluid has selection of different formations with different permeability, and oil and water [5-7]. At present, Foam fluid combined with CT is used in well intervention as a practical and cost-effective mean of servicing wells. Flow patterns of normal fluid can be understood with the aid of some software technology and computational fluid dynamics (CFD). The excellent properties of foam fluid are useful for drilling and development of reservoir, but it is difficult to simulate foam fluid which belongs to compressible Non-Newtonian Fluid.

2. CFD Model

FLUENT is a popular computational fluid dynamics software for modeling fluid flow and heat transfer in geometries. It makes it easy to solve flow problem with both structured and unstructured meshes. First, preprocessors are used for geometry modeling and mesh generation. Then, the model can be imported into FLUENT. The simulation can start after boundary conditions and initial conditions being set up.

2.1 Model Geometry and Grid Generation

GAMBIT has been a common tool for building the model geometry and meshing the model which is the preprocessor to FLUENT software where geometry is created, meshing is performed, and boundary conditions are established. In the present work, a 2-7/8” coiled tubing on a reel of 80” drum diameter is considered.

Meshing was performed by first meshing the edges of a circular face at one end of the fluid domain. Using the newly meshed edges, a boundary layer on the circular face was created to ensure that the wall of the CT was adequately resolved. Then the remainder of the face was meshed using the Pave face-meshing scheme shown in Fig. 1. After that, Using the inlet and outlet of the CT as source faces, the volume mesh was created by GAMBIT Cooper scheme. Then, the mesh was finished and can be exported for further analysis in FLUENT.

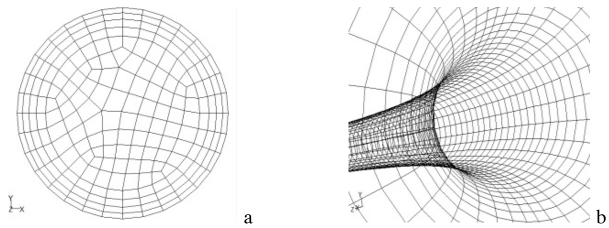

Fig. 1. (a) Grid of the tubing cross-section; (b) Inside view of the grid on the tubing wall.

3. Simulation Procedure

After the mesh is imported into the FLUENT solver, appropriate physical models such as laminar, turbulent or multiphase flow models need to be selected. The properties of the materials are defined. The boundary conditions can also be changed in the FLUENT. In the present work, the object of our study is foam fluid. The characteristics and the rheology of foam fluid should be described for further application.

3.1 Foam rheological characteristic

Foam fluid belongs to compressible Non-Newtonian Fluid. It has a lot of excellent properties, previous work shows that foam fluid can be described as Power-law fluid and it is suitable for using Power-law model (Eq.(1)).

$$\tau = K_a \gamma^n \tag{1}$$

Where, τ is share stress, K_a is the consistency coefficient ($Pa \cdot s^n$), n is the Power-law index, γ is shear rates. In order to better simulation foam fluid, the generalized consistency coefficient $K_a^{'}$ was introduced.

$$K_a^{'} = K_a \left(\frac{3n+1}{4n} \right)^n \tag{2}$$

$K_a^{'}$, n can be found in Table 1 as followed, Γ is the foam quality among the table.

Table 1. Relationship between foam quality and consistency coefficient and Power-law index.

foam quality	Generalized consistency coefficient	Power-law index
$96\% < \Gamma \leq 98\%$	$K_a' = 4.529$	$n = 0.326$
$92\% < \Gamma \leq 96\%$	$K_a' = 5.880$	$n = 0.290$
$75\% < \Gamma \leq 92\%$	$K_a' = 34.330\Gamma - 20.732$	$n = 0.7734 - 0.643\Gamma$
$65\% < \Gamma \leq 75\%$	$K_a' = 2.538 + 1.302\Gamma$	$n = 0.295$

3.2 Foam quality and density

Table 1 reflects the relationship between foam quality and foam rheology, in fact, foam quality decide foam rheology and density. Foam quality can be expressed by Eq.(3).

$$\Gamma = q_g / (q_g + q_l) \tag{3}$$

Where, q_g is gas flow rate, q_l is liquid flow rate. Foam density can be presented by Equation 4.

$$\rho_f = \Gamma \rho_g + (1-\Gamma)\rho_l \tag{4}$$

Where, ρ_f is foam density, ρ_g is gas density, ρ_l is liquid density.

Liquid flow rate of foam is almost constant, but gas flow rate changes with the change of pressure and temperature. Through user defined function in FLUENT, a program is written and foam density (quality) changes with pressure and temperature changing at every gird note.

4. Results and Discussion

4.1 Pressure and velocity distribution

Figure 2 shows that simulation result of the pressure along the helical coiled tubing at flow rate of 3 m/s. It can be observed that in this case, the highest point appears on the inlet of the tubing, and the pressure is reducing from entrance to export, negative pressure can even be found on the outlet.

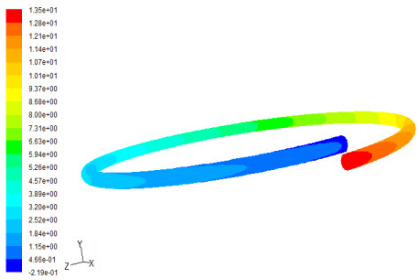

Fig. 2. Contours of pressure along the coiled tubing.

Figure 3 shows the simulation results of velocity on cross-section of the tubing. The sections was obtained by using a plane to cut the tubing vertically. As can be seen from the graph, the velocity closed outside of the helical coiled tubing is larger than that closed inside of it, the high velocity region is shifted toward the outer side of the tubing due to centrifugal forces. This will cause the secondary flow discussed later in this work.

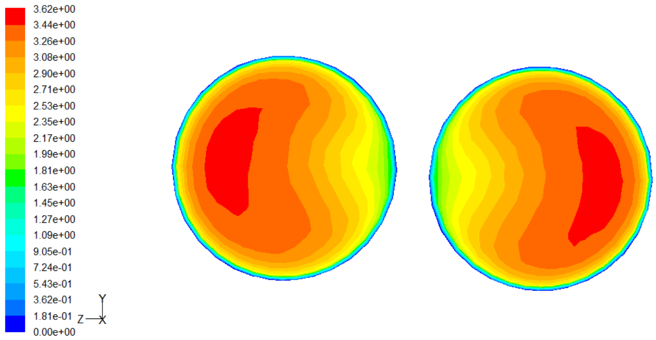

Fig. 3. Contours of velocity of the tubing cross-section.

4.2 Flow field and secondary flow

Figure 4 shows the flow field of the tubing cross-section. In order to contrast, water and foam are both simulated under the same conditions (mass flow rate). It is clear that the secondary flow appears in the cross section of the helical coiled tubing as vortex roll. In fact, the appearance of secondary flow is disadvantageous in the field application which contributes to resistance along the tubing. However, the configuration of vortex roll of foam fluid is smaller than that of water fluid because of foam's special properties and rheological characteristic, this phenomenon illustrates that foam can be used as a resistance reducing agent.

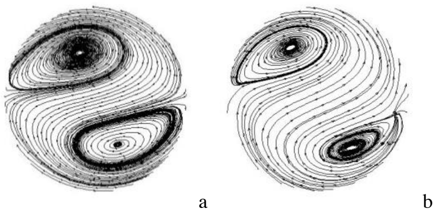

Fig. 4. (a) Flow field of water on the tubing cross-section; (b) Flow field of foam on the tubing cross-section.

5. Conclusions

(1) Pressure and velocity are reducing along the helical coiled tubing from entrance to export.
(2) The velocity closed outside of the helical coiled tubing is larger than that closed inside of it due to centrifugal forces.
(3) The secondary flow appears in the cross section of the helical coiled tubing as vortex roll, and the configuration of vortex roll of foam fluid is smaller than that of water fluid. Foam can be used as one kind of resistance reducing agents.

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